

Heralded Mapping of Photonic Entanglement into Single Atoms in Free Space: Proposal for a Loophole-Free Bell Test

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An obvious way to entangle two atoms located at remote locations is to produce a pair of entangled photons half-way between the two atoms, to send one photon to each location and to subsequently map the photonic entanglement into the atoms. The efficiency of this process is, however, fundamentally limited due to overall transmission losses. We propose a method to herald the success of the mapping operation in free space without destroying nor revealing the stored quantum state. Interestingly for a Bell test, the heralding signal does not open the detection loophole provided the measurement choice is performed once the heralding is obtained only. We show through a detailed feasibility study that this approach could provide an attractive alternative to Bell tests where the atom-atom entanglement is created from atom-photon entanglement using an entanglement swapping operation.

Motivation What can be more fascinating than the violation of a Bell inequality? Yet, the Bell game is simple, at least in principle. Two protagonists, Alice and Bob, share pairs of entangled particles. Each of them randomly chooses measurements, x and y respectively, among an appropriate set of two projectors ($\{x = 0, x = 1\}$ and similarly for y) and store the corresponding binary results, a and b ($\{a = +1, a = -1\}$ and similarly for b). They repeat the experiment several times until they can estimate the conditional probability distribution $p(ab|xy)$. The test really becomes exciting if the measurement results violate a Bell inequality, e. g. if [1]

$$\sum_{x,y=0}^1 (-1)^{xy} (p(a = b|xy) - p(a \neq b|xy)) > 2. \quad (1)$$

In this case, Alice and Bob are forced to conclude that the observed correlations are nonlocal, i. e. they got correlated results that are locally random, but cannot be reproduced by a shared randomness. All the Bell experiments realized so far point to the conclusion that this non-locality is, indeed, an element of the physical reality, but they were all subjected to loopholes.

There are basically two loopholes, the detection loophole and the locality loophole. The latter is closed if the measurement choice on Alice's side and the measurement result on Bob's side, and vice versa, are spacelike separated. If this condition is not fulfilled, the particles could simply communicate the measurement settings they experience to choose the results accordingly. The former is related to the inefficiency of detections. The particles could take advantage of the undetected events to answer when the measurement settings are in agreement with a predetermined strategy only. The locality

loophole was addressed in experiments with entangled photons [2] and the detection loophole with ions and photons [3–5]. Closing both in a single experiment would not only be the end of a long history of disputes, but like many fundamental findings, it would open the way to fascinating applications. For example, closing the detection loophole over tens of km would provide unique opportunities to quantum-key-distribution protocols where the security does not rely on the device that is used to generate the key [6].

State of the art Photons are naturally suited for closing the locality loophole. They are fast, easy to guide and can be produced at high repetition rates. However, the overall detection efficiency has to be higher than 82.8 % if one wants to close the detection loophole from the inequality (1), the so-called Clauser–Horne–Shimony–Holt (CHSH) inequality [1], with maximally entangled states. Considering realistic noise, achievable coupling into optical fibers and detection efficiencies, one rapidly becomes aware that closing the detection loophole with photons between spacelike separated locations is a very challenging task. Some looked for specific states or peculiar Bell inequalities offering a better resistance to inefficiencies [7]. Other studied the possibility of photonic Bell tests with homodyne measurements to overcome the problem of the single-photon detection inefficiency [8]. But the most promising approach for a loophole-free Bell test uses atom-photon entanglement [9], the photon allowing for the distribution of entanglement over long distances and the state of an atom being detected with an efficiency close to one. A lot of experimental effort has been devoted to the creation of a single photon from a single atom where the photon polarization is entangled with internal states of the atom [10–12]. Such entanglement has

further been used to entangle remote atoms through an entanglement swapping operation [4, 13, 14]. Hopefully, these impressive experimental results could lead to the first loophole-free Bell test in a near future.

Experimental activities investigating the resonant interaction in free-space of a single atom with single photons produced through the spontaneous parametric down conversion (SPDC) have emerged in parallel [15–17]. In ref. [18], the interaction of single heralded SPDC photons with a single atom has been demonstrated and in ref. [19], the possibility of obtaining atom–photon entanglement from the absorption by a single atom of a photon belonging to a polarization-entangled SPDC pair has been shown. One of the next great challenges could naturally be the creation of entanglement between remote atoms, by producing a pair of entangled photons half-way between two atoms and subsequently mapping the photonic entanglement into the atoms. The efficiency of this process is, however, fundamentally limited due to transmission losses. The mapping efficiency further decreases the entanglement creation rate. Ref. [20] proposed a way to herald the success of the entanglement creation by exciting a cycling transition and by detecting the resulting fluorescence detection. This heralding method has been implemented in ref. [21]. By further embedding the atoms in high-finesse cavities, the authors of ref. [20] end up with an efficient yet technologically demanding architecture for quantum networking. We here focus on free-space interaction and propose a fast and simple alternative method to herald the success of the mapping process without revealing the stored quantum state. Although the proposed heralding process is probabilistic, we show that it does not open the detection loophole provided that the heralding signal is obtained before the measurement choice. We believe that the proposed scenario is a potential candidate for the first loophole-free Bell test.

Heralded mapping of photonic entanglement into single atoms: Principle Consider the scenario presented in fig. 1 where two atoms, located at remote locations A and B, contain each a double Λ -system of levels. Further consider that they are initially prepared in a coherent superposition of two Zeeman levels

$$\psi_{i,+}^{\text{at}} = \frac{1}{2} (|i_+^A\rangle + |i_-^A\rangle) \otimes (|i_+^B\rangle + |i_-^B\rangle). \quad (2)$$

A photon pair source at a central station located half-way between two atoms is excited such that with a small probability p , an entangled pair is created, corresponding to a state

$$\left[1 + \sqrt{\frac{p}{2}} \underbrace{(a_+^\dagger b_-^\dagger - a_-^\dagger b_+^\dagger)}_{\sqrt{2}\psi_-^{\text{ph}}} + \mathcal{O}(p) \right] |0\rangle. \quad (3)$$

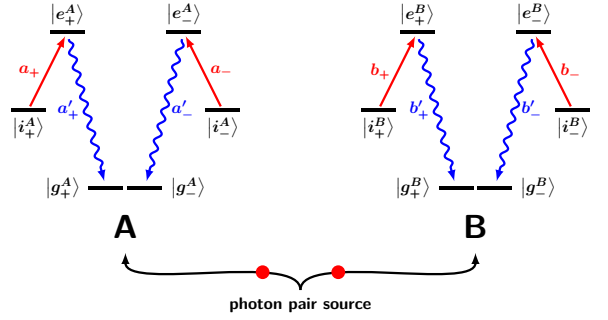


FIG. 1: Mapping polarization entanglement into the internal states of two atoms. The success of the absorption process is heralded locally by the detection of a single photon emitted spontaneously from an excited state. By choosing properly the detection basis, the heralding signal does not reveal the polarization of the absorbed photon and leads to the heralded creation of two entangled remote atoms. (See the main text for details).

Here, a_+ and a_- (b_+ and b_-) are bosonic operators associated to two orthogonal polarizations propagating towards Alice’s (Bob’s) location, e.g. in optical fibers, and $|0\rangle$ is the vacuum state. The $\mathcal{O}(p)$ term introduces errors in the protocol, leading to the requirement that p has to be kept small enough, cf. below. If a pair is created, the corresponding two photons can both be absorbed when they reach their destinations. Two successful absorptions transfer Alice’s and Bob’s atoms in excited states and map the photonic entanglement into an atomic entanglement $\psi_{\text{abs},-}^{\text{at}} = \frac{1}{\sqrt{2}} (e_+^A e_-^B - e_-^A e_+^B)$. In principle, the maximum achievable probability p_{abs} for a twofold absorption is equal to $\frac{1}{4} p \eta_t^2$, with η_t being the transmission efficiency from the source to one of the atoms. The pre-factor $\frac{1}{4}$ comes from the fact that out of the initial state (2), on average only every second photon can be absorbed. The coupling into the fiber η_c and the absorption efficiency η_{abs} further limit p_{abs} to $\frac{1}{4} p \eta_c^2 \eta_t^2 \eta_{\text{abs}}^2$.

Once they are excited, the atoms can spontaneously decay into ground states g_+^A or g_-^A (g_+^B or g_-^B) by emitting a photon with the corresponding polarization a'_+ or a'_- (b'_+ or b'_-), i.e.

$$\psi_{\text{em},-}^{\text{at}} = \frac{1}{\sqrt{2}} (g_+^A g_-^B a'_+ b'_- - g_-^A g_+^B a'_- b'_+) |0\rangle. \quad (4)$$

Hence, the detection of one spontaneous photon at each location serves as a heralding signal for the success of the mapping process and moreover, the entanglement is preserved if the re-emitted photons are detected in the appropriate basis. For example, the detection of two photons, one with the polarization $a'_H = \frac{1}{\sqrt{2}} (a'_+ + a'_-)$ and the other with $b'_H = \frac{1}{\sqrt{2}} (b'_+ + b'_-)$, projects the state of

the atom pair into

$$\psi_{\text{herald},-}^{\text{at}} = \frac{1}{\sqrt{2}} (g_+^A g_-^B - g_-^A g_+^B). \quad (5)$$

The probability to obtain the heralding signal after absorption is η_d^2 where η_d is the efficiency with which a spontaneous photon is detected from a single atom. Since twofold detection in $\{a'_V, b'_H\}$, $\{a'_H, b'_V\}$, $\{a'_V, b'_V\}$ also projects the two atoms into $\psi_{\text{herald},-}^{\text{at}}$ (up to a unitary), the overall heralding efficiency is given by $p_{\text{herald}} = \frac{1}{4} p_{\text{lc}}^2 \eta_t^2 \eta_{\text{abs}}^2 \eta_d^2$.

After the detection of the heralds, Alice and Bob can choose their measurement setting, i.e. they perform a rotation on the two level system $\{g_+, g_-\}$ before measuring the state of their atom through state-selective fluorescence (electron shelving) or ionization. To close the locality loophole, it is important that the distance L separating Alice and Bob is such that L/c (where c is the velocity of light in vacuum) is larger than the time it takes to know the atomic state once the measurement setting is chosen. Independent of this is the other characteristic time scale, i.e. the time it takes to receive a twofold herald, which can be very long.

We emphasize that the heralding process does not open the detection loophole if Alice and Bob choose the measurement settings x and y only after the spontaneously emitted photon is detected. This simply reduces to a pre-selection and none of the inefficiencies mentioned so far enters in the detection efficiency required to close the detection loophole. In particular, contrarily to the situation without pre-selection, there is no limitation (other than technical ones) on the efficiency with which the photon states are mapped to the atoms, if one is willing to lower the atomic entanglement-creation rate [22]. Note also that Alice does not need to know whether Bob got the heralding signal when she chooses her measurement setting. The detection of one spontaneous photon at each location decides that a given run is going to contribute to the data of the CHSH inequality test, and the measurement settings can be determined locally from the polarization of the detected photon.

Heralded mapping of photonic entanglement into single atoms: Practical implementation We now discuss a practical implementation of the heralded entanglement distribution and Bell test in more detail. For concreteness, we consider implementing the scheme using two distant single trapped and laser-cooled $^{40}\text{Ca}^+$ ions. The $^{40}\text{Ca}^+$ ion is the only single atomic system so far which has been coupled to entangled SPDC photons [17–19]. A scheme of its relevant atomic levels and transitions is shown in fig. 2. Based on the experimental work reported in [15–19] we assume that the entangled photons are created at 854 nm, resonant with the transition from

the metastable $D_{5/2}$ level to $P_{3/2}$. Photon loss in optical fibers at this wavelength is of the order of 1 dB/km. This means that for $L = 3$ km, both photons will reach Alice's and Bob's locations with a probability $\eta_t^2 \approx 0.5$. This also translates into an upper bound for the time delay between the measurement choice and the measurement result of 10 μs . The heralding photons are assumed to be emitted on the $P_{3/2}$ to $S_{1/2}$ transition at 393 nm. The other levels and transitions presented in fig. 2 are employed for state preparation and detection [21].

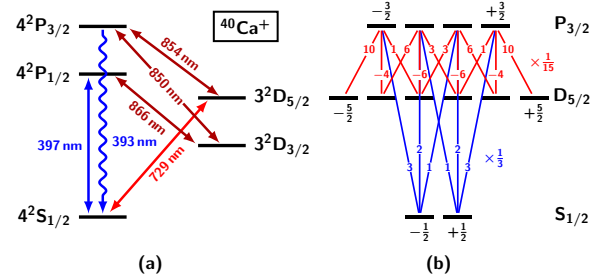


FIG. 2: (a) Level scheme and transitions for the $^{40}\text{Ca}^+$ ion. The branching ratios for the decay of $P_{3/2}$ are 94 % into $S_{1/2}$, 6 % into $D_{5/2}$, and < 1 % into $D_{3/2}$. (b) Clebsch–Gordan coefficients (CGC); the CGC of a particular $m \rightarrow m'$ transition is obtained by multiplying the modulus of the respective number with the factor on the right, taking the square root, and applying the sign indicated with the number.

A weak magnetic field \vec{B} defines a quantization axis and thereby, together with the direction of propagation of the incoming photons \vec{k} , possible polarization bases [19]: when $\vec{k} \parallel \vec{B}$, absorption of circularly polarized photons leads to $\Delta m = \pm 1$ transitions; when $\vec{k} \perp \vec{B}$, photons with polarization $\vec{\epsilon} \parallel \vec{B}$ induce $\Delta m = 0$ transitions, and photons with $\vec{\epsilon} \perp \vec{B}$ drive a superposition of the two $|\Delta m| = 1$ transitions.

The initial state (2) is implemented by preparing each atom in a coherent superposition of sublevels $|D, \pm \frac{5}{2}\rangle$ in $D_{5/2}$. This is achievable, for example, by coherent excitation on the $S_{1/2}$ to $D_{5/2}$ quadrupole transition used as optical qubit in quantum logic experiments. More precisely, this superposition can be produced starting from $S_{1/2}$ after cooling the ion and optical pumping into a single $|S, m\rangle$ sublevel, by employing a Rabi $\pi/2$ -pulse on $|S, -\frac{1}{2}\rangle \rightarrow |D, -\frac{5}{2}\rangle$, followed by a Rabi π -pulse on $|S, -\frac{1}{2}\rangle \rightarrow |S, +\frac{1}{2}\rangle$ (at radio frequency) and a subsequent Rabi π -pulse on $|S, +\frac{1}{2}\rangle \rightarrow |D, +\frac{5}{2}\rangle$. The whole state preparation requires less than 25 μs .

Then, the ions are exposed to the photons at 854 nm. The final state (4) after emission of the heralding photon involves the magnetic sublevels of the $S_{1/2}$ state. Faithful mapping of the absorbed photon to the atomic state requires that the two emission pathways

be indistinguishable. Since they happen on transitions with different Δm , the corresponding photons have to be projected on the same emitted polarization $\vec{\epsilon}_{393}$, as mentioned in the previous section. Detection in this case is optimal along the quantization axis in a linear polarization basis; by using two detectors for two orthogonal polarizations, the highest possible efficiency η_d will be obtained.

Current experiments [21, 23] achieved the values $\eta_{\text{abs}} = 2.5 \cdot 10^{-4}$ and $\eta_d = 1.55\%$ (using a photon collection of 5.5% and photon detectors with an efficiency of 28%). By using parabolic mirrors [24] to enhance the coupling to near unity, a maximal value of $\eta_{\text{abs}} \approx 6\%$ can be achieved (limited by the oscillator strength of the transition, cf. fig. 2) while η_d can be of the order of 30%. Furthermore we assume that $\eta_c = 70\%$. All these numbers together yield an efficiency p_{herald} of the order of $2 \cdot 10^{-5}p$.

Expected atom-atom entanglement visibility Taking the main experimental limitations into account, we now estimate the fidelity of the heralded atom-atom entangled state with respect to the singlet state (5). Our approach starts with the emission of photon pairs. Due to possible multiple pair emission inherent in SPDC processes, the photon-photon entangled state can be written $\rho^{\text{ph}} = V^{\text{ph}}|\psi_-^{\text{ph}}\rangle\langle\psi_-^{\text{ph}}| + (1 - V^{\text{ph}})\frac{\mathbf{1}}{4}$ where $\mathbf{1}$ stands for the identity and $V^{\text{ph}} = \frac{1-p/2}{1+p/2-p^2/2} \approx 1 - p + \mathcal{O}(p)$ [25] is the visibility of the interference that would be obtained if Alice chooses the measurements σ_x for example and Bob rotates his measurement basis in the $\{xz\}$ plane. Additional errors (with corresponding probability e) occurring at the further stage of the experiments degrade the visibility according to $V \rightarrow (1 - e)V$. Once a photon pair is created, it propagates to Alice's and Bob's locations. We assume that the polarization is actively controlled such that the error on the polarization is of the order of $e_{\text{pol}} = 1\%$. The photonic state is then mapped to the atoms. The heralded mapping operation (one photon to one atom) is estimated to be inaccurate at the same order, $e_{\text{map}} = 1\%$. Dark counts of the heralding detectors add negligible noise. The dominant error happens when one detector clicks because of a photon detection but the other one produces a dark count. The probability of this erroneous event is given by $p_{\text{dark}} = p\eta_c\eta_t\eta_{\text{abs}}\eta_d\eta_{\text{dark}}$ where $\eta_{\text{dark}} = R_{\text{dark}}\Delta t$, R_{dark} being the dark count rate (assumed to be 30 counts per second) and Δt is the coincidence window (up to 20 ns with respect to the photon coherence time of 7 ns). The corresponding error is given by $e_{\text{dark}} = \frac{p_{\text{dark}}}{p_{\text{dark}} + p_{\text{herald}}} \leq 10^{-3}$. The resulting atom-atom entangled state is thus expected to be of the form

$$\rho^{\text{at}} = V^{\text{at}}|\psi_{\text{herald},-}^{\text{at}}\rangle\langle\psi_{\text{herald},-}^{\text{at}}| + (1 - V^{\text{at}})\frac{\mathbf{1}}{4} \quad (6)$$

where the visibility of the atomic entanglement is given by $V^{\text{at}} = V^{\text{ph}}(1 - e_{\text{pol}})(1 - e_{\text{map}})^2(1 - e_{\text{dark}}) \approx 0.97(1 - p) + \mathcal{O}(p)$.

Performing the Bell test Once the heralding signal is obtained, Alice (or Bob) needs to be able to detect the state of her (his) ion in various bases. The necessary rotations between $|S, +\frac{1}{2}\rangle$ and $|S, -\frac{1}{2}\rangle$ are performed in up to 10 μs by a magnetic field at radio frequency. The detection then proceeds by electron shelving of one $S_{1/2}$ sublevel into $D_{5/2}$ and measuring resonance fluorescence from the $S_{1/2} \leftrightarrow P_{1/2}$ transition. Following ref. [26], such a measurement takes in average 145 μs with a photon collection of 0.22% and the mean accuracy of this procedure was experimentally determined to be 99.99%. However, assuming a global detection efficiency of $\eta_d = 30\%$ as before, the measurement time reduces to the time it takes to perform to the local rotation (10 μs). This is fast enough to close the locality loophole with a distance of 3 km. The measurement accuracy could realistically be of $1 - e_{\text{det}} = 99.95\%$.

Expected violation of the CHSH inequality The resulting CHSH value is expected to be given by

$$S_{\text{exp}} = 2\sqrt{2}V \quad (7)$$

with the statistical uncertainty

$$\Delta S_{\text{exp}} = \frac{1}{\sqrt{2N}} \times \sqrt{3(1 - \frac{1}{\sqrt{2}}V)^2(3 + \frac{1}{\sqrt{2}}V) + (1 + \frac{1}{\sqrt{2}}V)^2(3 - \frac{1}{\sqrt{2}}V)}$$

where V stands for $V^{\text{at}}(1 - 2e_{\text{det}})^2$ [27]. In principle, the value of p needs to be optimized since a high CHSH value favors $p \approx 0$ whereas a high heralding probability favors $p \approx 1$. However, practical considerations limit the pair production to approximately $5 \cdot 10^5$ per seconds, i.e. $p = 4 \cdot 10^{-3}$ for $\Delta t = 7$ ns. This leads to $V^{\text{at}} \approx 96\%$ and $S_{\text{exp}} \approx 2.73$ so that $N = 65$ events are necessary to conclude about the violation of the CHSH inequality with a confidence level above 99.7% (3 standard deviations). The duration of the state preparation ($T \approx 25 \mu\text{s}$) mainly defines the repetition rate and this translates into an overall acquisition time of $NT/p_{\text{herald}} \approx 6$ hours and 30 minutes.

In order to rule out local models as plausible explanations of an observed Bell inequality violation, it is convenient to estimate the probability that the observed statistics be produced by such a model [28, 29]. Since the deviation of the Bell values that can be obtained by local models in presence of finite statistics need not be described appropriately by the experimental uncertainty ΔS_{exp} , we rely on the following bound [29]:

$$P(S_{\text{exp}}|\text{local model}) \leq \exp(-N(S_{\text{exp}} - 2)^2/32). \quad (8)$$

This quantity is bounded by 0.05 for the above value of S_{exp} , whenever $N > 181$. A clear demonstration that the observed statistics are not the result of a local model is thus possible in a bit more than 18 hours.

Conclusion Our proposal opens a way to test Bell's inequalities in a loophole-free realization. Specifically, it offers an interesting alternative to Bell tests where atom-atom entanglement is created by means of an entanglement swapping operation. The latter is being pursued by several groups and recent advances are very promising [4]. Time will tell which one will allow one to answer a question lively debated about non-locality. From a more applied perspective, our proposal could find applications in quantum key distribution, either for implementing more secure protocols [6] or for extending quantum key distribution over thousands of kilometers using quantum repeaters [20, 30, 31].

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